END-TO-END COMMUNICATION TEST ON VARIABLE LENGTH PACKET STRUCTURES UTILIZING AOS TESTBED

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Abstract

This paper describes a communication test, which successfully demonstrated the transfer of losslessly compressed images in an end-to-end system. These compressed images were first formatted into variable length Consultative Committee for Space Data Systems (CCSDS) packets in the Advanced Orbiting System Testbed (AOST). The CCSDS data Structures were transferred from the AOST to the Radio Frequency Simulations Operations Center (RFSOC), via a fiber optic link, where data was then transmitted through the Tracking and Data Relay Satellite System (TDRSS). The received data acquired at the White Sands Complex (WSC) was transferred back to the AOST where the data was captured and decompressed back to the original images. This paper describes the compression algorithm, the AOST configuration, key flight components, data formats, and the communication link characteristics and test results.

1.0 INTRODUCTION

With the advent of sophisticated scientific satellites, space data communication systems are becoming more complicated in order to handle advanced instruments which generate variable data rates and formats. The desire to provide international cross-support across different platforms in order to better utilize the science data globally has prompted the international CCSDS to issue a recommended standard on space data system architecture specified in the Advanced Orbiting System (AOS) Blue Book [1]. This architecture provides flexibility to transport space data between platforms, ground stations and commercial data networks. To demonstrate the capability of this architecture, Goddard Space Flight Center (GSFC) has been developing a testbed for the AOS. The key components of the AOST is implemented in hardware in order to provide insight regarding achievable speed and limitations for actual flight hardware. The block diagram in Figure 1 shows these key components including an instrument simulator followed by a packet generator, a high-speed multiplexer, additional instrument simulators, and a virtual channel transfer frame generator.

The testbed is capable of implementing the packet data architecture specified in the standards book and re-illustrated in Figure 2. A salient feature of the data architecture is the ability to transport variable-length CCSDS packet, as opposed to the conventional fixed-length packet structures. This structure allows packet data from different instruments to be multiplexed in a much more flexible way in the data system. For data originating from one single instrument, the variable-length packet is also a natural structure for holding the variable-length bit string resulting from losslessly compressing fixed-length instrument data, such as from a scan line of image data.

In parallel with AOST effort, GSFC is also engaged in the development of data compression technology. Data compression provides a viable means to alleviate the demands on onboard storage, communications bandwidth, station contact time and ground archive requirements. There are two types of data compression: a lossless technique, which guarantees full reconstruction of the data; and a lossy technique, which generally gives higher data compaction ratio but incurs distortion in the reconstructed data. Lossless compression generally results in variable length compressed data due to statistical nature of the original data. To satisfy the many science disciplines, lossless data compression has become the priority for development. After extensive research, the Rice algorithm [2,3] was chosen and developed into hardware. In 1991, a hardware engineering model was built in an application specific integrated circuit (ASIC) for proof of concept. This particular chip set was named the Universal Source Encoder/ Universal Source Decoder (USE/USD) (Venbrux, 92)[4]. Later, it was redesigned with several additional capabilities and implemented in Very Large Scale Integration (VLSI) circuits using gate arrays suitable for space missions. The flight circuit is referred to as Universal Source Encoder for Space (USES). The fabricated USES chip is capable of processing data up to 20 Msamples/second and will take data of quantization from 4-bit to 15-bit [5]. In the following sections, we will provide a brief description of the data compression algorithm, the overall communication system, the AOST and physical link characteristics.

2.0 THE LOSSLESS DATA COMPRESSION ALGORITHM

The architecture of the Rice algorithm is shown in Fig. 3. It consists of a preprocessor to decorrelate data samples and subsequently map them into symbols suitable for the entropy coding module. This entity is a collection of options operating in parallel over a large entropy range. The option yielding the least number of coding bits will be selected. This selection is performed over a block of J, typically 16, samples to achieve adaptability to scene statistics. An identification field of a fixed number of bits, determined by the input sample quantization levels, is used to signal the selected option for the block. The performance of this algorithm has been shown to be the same as that of a collection of Huffman codes on typical imagery [6] and has been tested on various instrument data [7].

3.0 SYSTEM DESCRIPTION

3.1 End to End System Description

The end-to-end system is depicted in Figure 4. The AOST is linked via an optical fiber to the RF SOC, which transmits the packetized data to the White Sands Complex (WSC) via a TDRS on a Ku band carrier. Data was recorded at the WSC and later transmitted to the AOST via NASA communication (NASCOM).

3.2 Source Equipment

3.2.1 Data Source

The source data can be either simulated instrument data or a video frame of data acquired from a CCD camera. In both cases, the data is first loaded into a frame buffer before each scan line is passed to the compression hardware which incorporates the USE chip. Each compressed scan line is then passed to the packetizer for further processing.

3.2.2 Packetizer and Multiplexer System Description

The packetizer takes data from the instrument, encapsulates it into CCSDS packets [8], and sends them over a fiber optic transmitter- receiver interface (FOXI) at a burst transfer rate of 80 Mbps. A separate packet is formed for each video scan line with the segmentation flag in the packet header used to treat an entire video frame as a large data block. The segment flag is set to "beginning of segment" for the first scan line of a video frame; it is set to "continuation segment" for intermediate scan lines; and it is set to "end of segment" for the final video scan line of a video frame. Frame synchronization is derived through control signals in the FOXI interface.

The multiplexer operates in two modes: 1) path service mode where the multiplexer passes CCSDS packets through to the Wideband Transfer Frame Formatter (WTFF) without processing and 2) virtual channel access (VCA) service mode where the multiplexer produces multiplexing protocol data units (MPDU) and transmits them to the WTFF. Access to the output channel is granted based on availability and a round robin polling sequence. This polling occurs once every 400 ns, which is rapid enough that it results in a statistical multiplexing function. In general, the higher the packet rate for a channel, the more the number of requests and grants are given to that channel, causing access to be data rate driven. Details of the hardware are provided in [9].

3.2.3 Wideband Transfer Frame Formatter (WTFF)

The WTFF system [10] is designed to serve as a gateway providing transfer frame generation using a subset of the AOS services, as defined in Reference 1, for up to seven user virtual channels (VC) plus an idle channel. Data messages arriving from any one of the user VCs are buffered and then inserted into CCSDS standard format data transfer frames. These frames are padded with frames from the idle channel as necessary to maintain a preset data rate and are output on a single serial line. CCSDS Grade-2 service is provided by including a Reed-Solomon (RS) (255,223) error correcting code in each of the eight virtual channel circuits to form coded virtual channel data units (CVCDUs formed from VCDUs or MPDUs, Fig. 2).

Virtual Channel: A VC unit receives user data and formats it into virtual channel frames (i.e., CVCDUs) at rates up to 100 Mbps. The frames are composed of five interleaved RS code words containing 255 bytes each. Each CVCDU is thus 1275 bytes (10,200 bits) long, including the RS encoding check symbols. When CVCDUs are appended with a frame synchronization pattern (32 bits), a channel access data unit (CADU) is created, which can be transmitted over I or Q output data streams. Each VC is configured by the system controller upon initialization or during system re-configuration and has a unique ID (VCID) set by hardware. Data can be received as a fixed length data unit (MPDU in VCA service) or as CCSDS packets (Path Service).

PN Code Transition Generator: To ensure bit transition, the pseudo-noise (PN) transition generator is utilized. When it is, each byte of the CVCDU is XORed with a stored PN pattern before being sent through the multiplexer to the I or Q data outputs. The frame synchronization pattern is generated separately and is neither RS coded or changed by the PN generator.

3.3 Data Capture Equipment

All packetized data received at the WSC on the I channel was transferred to a workstation and processed predominantly with software tools. The Q channel signal was sent to a communications bit error rate (BER) test set for real time monitoring. The capture and analysis equipment is composed of a 32 Mbyte solid state memory connected to a Sun workstation via an ethernet; frame detection software; a hardware RS decoder; a software RS encoder; virtual channel and packet detection software; a software data decompressor; and a software image display package for the workstation.

3.3.1 Frame Detector

The original data as organized into frames by the WTFF is a series of bytes forming a data frame structure. Once transmitted from the WTFF, the bits in each byte are serialized and knowledge of the byte boundary is lost. The frame detection software searches the received file on a bit by bit basis to find the frame synchronization marker. To ensure that it is the frame marker and not a sequence of data bits that happened to be the same as the frame marker, the file position pointer was moved one frame length from the initial marker and data was examined for a second marker. In all of the data collected, a bit slip (or bit addition) was never observed, making the need for a more elaborate frame synchronization strategy unnecessary.

3.3.2 Reed Solomon Decoding

After byte alignment and frame detection, RS decoding was performed. Each frame output from the RS decoder has a 16-byte status block appended to it. During the data flow with the compressed variable length image packets, the error rates were never severe enough to cause uncorrectable frames. During the portion of the test where the purpose was to evaluate the Ku band physical link using the CCSDS structure, frames that were found to be uncorrectable were not deleted. They were examined for burst error statistics along with the correctable frames. When uncorrectable frames occurred, the data portion of the frame was corrected by computer using knowledge of the data structure, and the parity portion was generated by re-encoding the data. CCSDS idle frames were also retained and RS decoded. The received raw data was compared with RS corrected data to determine burst error statistics.

3.3.3 Channel and Packet Detection

The file created after RS decoding was then processed by a software program called CHANNEL which examined the CCSDS frame header and produced a separate output file for each virtual channel identification (VCID) number that was found. Compressed video packets were assigned a particular application identification (APID) on a particular virtual channel. The PACKET program was run on the VCID file of interest and produced separate output files for each APID found in that VC. The APID file of interest contained variable length packets of compressed video data.

3.3.4 Decompressor

The packet file associated with the image frame data was further broken down into a separate file containing one compressed image frame. These 512 variable-length lines were decoded to generate one fixed-length image frame. In software, this decoding routine performed the decompression algorithm and simulated the operation performed by the Universal Source Decoder (USD) chip, realizing the lossless data decompression algorithm. The routine used the reference sample at the start of each compressed 512 sample line as well as the header information at the start of each compressed 16 sample block to convert the data back to its uncompressed format. The resulting 512x512x8 bit binary image file was then accessed by a commercial display software package.

4.0 TEST PARAMETERS AND LINK ANALYSIS

4.1 Test Parameters

Testing of the AOST using variable length packet structures was performed by using losslessly compressed images. The first image transmitted was a prestored Landsat image. After the Landsat image was received, real time images from the video camera and packetized data from the simulators were routed through the source equipment and output on the WTFF I channel at 80 Mbps while the WTFF Q channel was not used. PN data transmitted on the RF Q channel was used to monitor the link BER. The WTFF I channel was configured to run at a continuous output rate of 80 Mbps (including idle channel fill frames) by using an 80 MHz crystal on its high speed output board. The WTFF configuration was as follows:

Virtual Channel #	Virtual Channel Mode	Data Source	Data Rate
1	Path Service	Simulator	16.0 Mbps
2	VCA Service	CCD camera	~28 Mbps
3	Path Service	Simulator	16.0 Mbps
63	Idle channel	WTFF	as needed

4.2 Link ANALYSIS

In addition to evaluating compressed variable length packets, this test allowed an examination of the channel characteristics of the K-band Single Access (KSA) return link through TDRSS. The primary objective was to evaluate a BCH code proposed for a LANDSAT-7 300 Mbps return link.

It was important to understand the error characteristics of the channel because the proposed binary BCH code (1023,993,3) can only correct 3 bit errors in a block of 1023 bits. This section will concentrate on the performance of the link used in this experiment in terms of BER vs. Eb/No. Link analysis was performed by transmitting a PN data pattern of NRZ-M data at 300 Mbps, QPSK modulated (150 Mbps on I, 150 Mbps on Q) through the KSA return channel. The data was recorded in one minute samples, and six pairs of C/No and BER measurements were taken at WSC with 2^{23}-1 and 2^{7}-1 PN coded data. The measurements are summarized in Table 1. Using the measured carrier to noise density, the required effective isotropic radiated power (EIRP) values were also calculated.

TABLE 1. C/No, BER and RF SOC EIRP Data Points

Measured C/No (dB)	Measured Bit Error Rate	EIRP Required for Measured C/No
95.1	0.8e-3	51.2
95.3	3.5e-4	51.4
96.5	9.0e-5	52.6
98.9	2.0e-5	55.0
99.3	3.0e-6	55.4
99.9	2.0e-7	56.0

A plot of the six data points are shown in Figure 5 along with the ideal BER vs. Eb/No curve. The separation from the ideal curve varied with each measurement, about an average of 3.6 dB foı five of the data points. This value was taken as the implementation loss. It is important to note that for the required EIRP calculation, several loss parameters were assumed based on estimates and the weather conditions of that day (which was cloudy with light rain) at the transmit site.

5.0 RESULTS

Since the WTFF used the CCSDS recommended (255,223) RS code, it was expected that as long as the BER was about $1*10^{-4}$ or better, the RS decoding would correct all of the errors. It was therefore expected that the decompression process would be error free and the reproduced image would be identical to the digital version of the original. This was found to be true.

5.1 Image Quality

No streaks or drop outs occurred in the images. Since the compression technique was applied independently to each scan line, a decompression error would be expected to corrupt an entire line. Loss of a user data CCSDS frame would impact several image lines, but no corruptions were observed.

5.2 Channel Performance

One of the concerns was to evaluate the burst errors on the TDRS Ku band link. A test cannot examine all the parameters that vary over a satellite's lifetime, but it can at least provide a snapshot of some of those parameters. In order to simulate an end-to-end system, the data was recorded at the WSC and retransmitted to GSFC before being finally decoded.

During the link portion of the test, differential coding (NRZ-M) was used to avoid data inversion. The disadvantage of NRZ-M is that it causes each error to appear as two errors which may or may not be consecutive. In the data observed, no errors greater than 2 bits in length (errors were always consecutive) were observed when the proposed Landsat 7 power level was used. At lower power settings, where the BER was greater, longer burst lengths were seen (Table 2). For this analysis, a burst was arbitrarily defined as a group of incorrect and correct bits where there were no more than 11 consecutive correct bits. A burst always starts and ends with an error.

TABLE 2. BER vs. Error Burst Characteristics

BER	Max Length of Burst	Max Errors Per Burst
2.2e-5	2	2
1.3e-4	14	4
8.5e-4	22	6

The CCSDS frame sequence count was continuous with no gaps. Bit slips (or additions) were never observed in this or other AOST tests with the TDRSS.

6.0 CONCLUSION

The CCSDS recommendations for AOS data architecture have been put to a physical test with compressed data being multiplexed with several separate instrument channels. Losslessly data compressed images were received and decompressed without any distortion. The achieved compression ratio is about 1.8 for the Landsat image. This type of compressed data is very sensitive to channel errors which, if they occur, cause long streaks in the recovered images as results of the decompression operation. Therefore one can say that the data generation and recovery system worked as expected. No problems were introduced by the variable length packets resulting from lossless compression. The Ku band TDRSS link contained errors consistent with a purely thermal (random) environment for data transmitted from the GSFC. This analysis is based on statistics gathered during a short period, therefore no statement can be made about the burst environment that would be observed when the TDRSS antenna is pointed toward other areas of the Earth.

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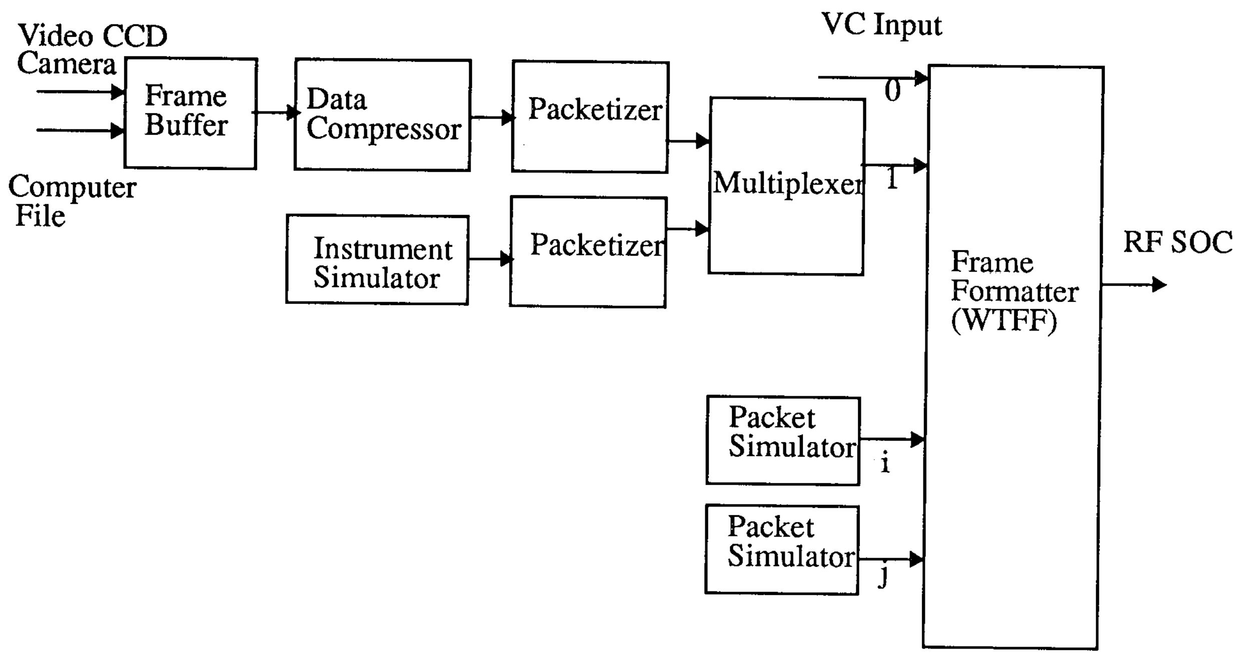

Figure 1. AOS Test Bed Key Components

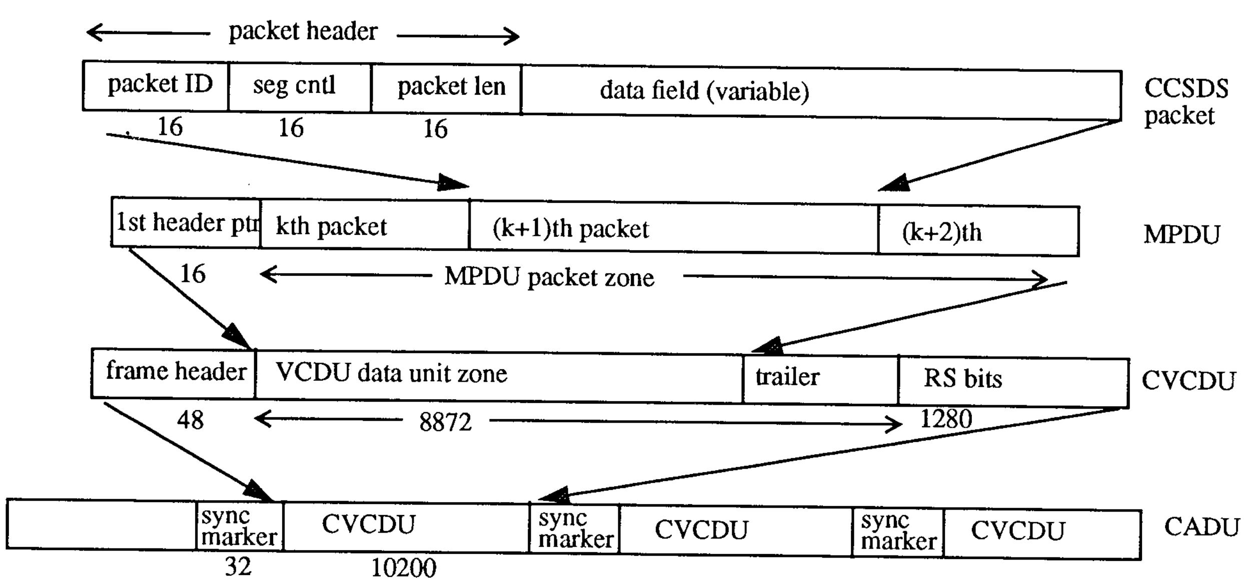

Figure 2. CCSDS Data Unit Structure

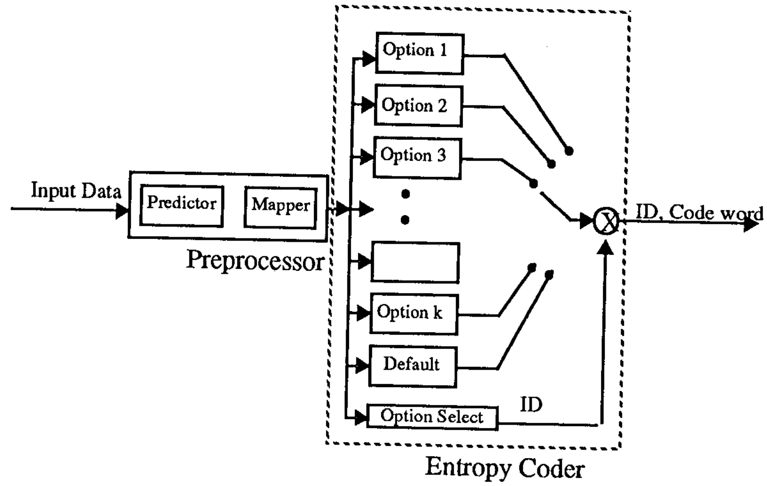

Figure 3. Rice Compression Algorithm

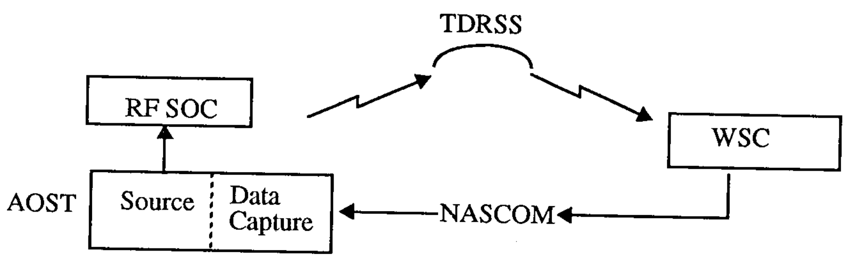

Figure 4. End to End Test Block Diagram

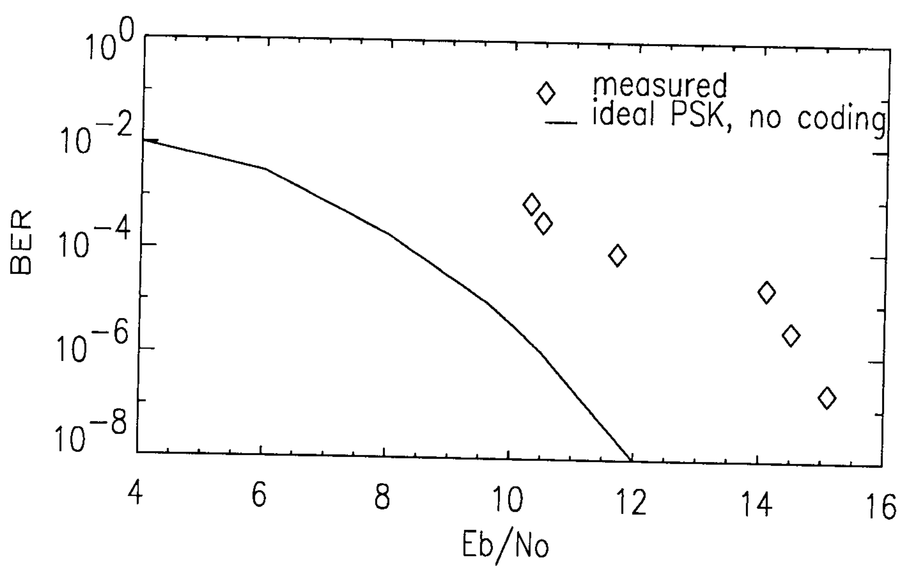

Figure 5. End-to-End Test BER vs. Eb/No